

Airflow Hazard Visualization for Helicopter Pilots: Flight Simulation Study Results

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Abstract

Airflow hazards such as vortices or low level wind shear have been identified as a primary contributing factor in many helicopter accidents. US Navy ships generate airwakes over their decks, creating potentially hazardous conditions for shipboard rotorcraft launch and recovery. Recent sensor developments may enable the delivery of airwake data to the cockpit, where visualizing the hazard data may improve safety and possibly extend ship/helicopter operational envelopes. A prototype flight-deck airflow hazard visualization system was implemented on a high-fidelity rotorcraft flight dynamics simulator. Experienced helicopter pilots, including pilots from all five branches of the military, participated in a usability study of the system. Data was collected both objectively from the simulator and subjectively from post-test questionnaires. Results of the data analysis are presented, demonstrating a reduction in crash rate and other trends that illustrate the potential of airflow hazard visualization to improve flight safety.

Introduction

The dangers that airflow hazards pose to helicopter pilots may be mitigated by new hardware developments that can provide airflow data to the cockpit. The challenge then becomes how to concisely present this large volume of data to the pilot. We discuss the process of user-centered design by which a prototype of an airflow hazard visualization system was developed. We describe the system implementation, and the protocol, methodology and results of a flight simulation usability study. The presence of the visual system dramatically reduced the crash rate for helicopters flying into simulated hazardous conditions.

Airflow Hazards

Turbulence and other wind-related factors were implicated in nearly 10% of the over 21,000 aircraft accidents in the US National Transportation Safety Board accident database from 1989-99 [1]. Encounters with airflow hazards such as vortices, downdrafts, low level wind shear, microbursts, or turbulence from surrounding vegetation or structures near the landing site can be deadly to aircraft of all categories and classes. However,

helicopters are especially vulnerable to airflow hazards because they often have to operate in confined spaces and under operationally stressful conditions (such as emergency search and rescue, military or shipboard operations).

Airflow hazards are hard to detect simply because air is invisible. Disturbed airflow is undetectable by pilots on a landing approach unless the air happens to pick up dust, smoke or other aerosols that are visible to the human eye. Being thus unable to directly see a factor of potentially great importance to them, pilots learn to use their intuition to predict airflow patterns over obstacles near the takeoff or landing site, and they learn to pick up visual cues from the surrounding area. However, airflow-related accidents still occur.

Helicopter Shipboard Operations

Operating a helicopter from a moving aircraft carrier is one of the most demanding tasks a helicopter pilot can face [2, 3]. The pilot must maneuver the helicopter within very tight tolerances to avoid striking ship structures or other aircraft. In addition, high sea states may cause extreme deck angles of pitch and roll, and low visibility may degrade visual cues. Furthermore, because the ship is moving, its superstructure will always generate an airwake consisting of vortices and other airflow hazards, adding to the challenge of shipboard launch and recovery. It is a task

that demands the utmost concentration and skill from the pilot. A system that can deliver even an incremental amount of assistance to the pilot could yield a significant safety improvement in this domain.

Helicopter accidents and incidents that occur on shipboard range from incidents such as tunnel strikes to fatal accidents. Over 120 tunnel strikes have occurred in dual-rotor helicopters since the 1960s, causing damage ranging from \$50K to over \$1M per incident [4]. Analysis of these accidents and incidents frequently finds airflow hazards to be the root cause. The pilot and ground crew are initially unaware of the danger, and the pilot is unable to react in time. Presenting the appropriate information that could enable the flight crew to make correct decisions in advance of the hazard encounter, therefore, could reduce or prevent such accidents.

Because shipboard rotorcraft operations are such a demanding environment, the US Navy's Dynamic Interface flight test program has compiled significant amounts of data from shipboard flight tests, wind tunnel tests, and computational fluid dynamics computations studying the aerodynamics of shipboard-rotorcraft interactions [5].

Conveying Ship Airwake Information to Pilots

The current method of communicating this information to the pilots consists of publishing pre-computed operational envelopes (Figure 1) listing allowable wind conditions for many ship-rotorcraft combinations [6, 7]. The envelope conveys a go/no-go decision, and does not state which safety considerations motivate a given operational limit. Pilots check the published envelope for their helicopter before beginning any approach, and they fly the approach only if they are within the envelope. This procedure has the advantage of providing clear, simple direction to the pilots under all wind conditions. However, if the winds shift out of the envelope during the approach, or some other event occurs that changes the airflow over the landing site, such as a helicopter on an upwind spot starting up its rotor, a hazardous condition can occur of which the pilot is unaware. This type of situation has been demonstrated to be a causal factor in many accidents and incidents [8].

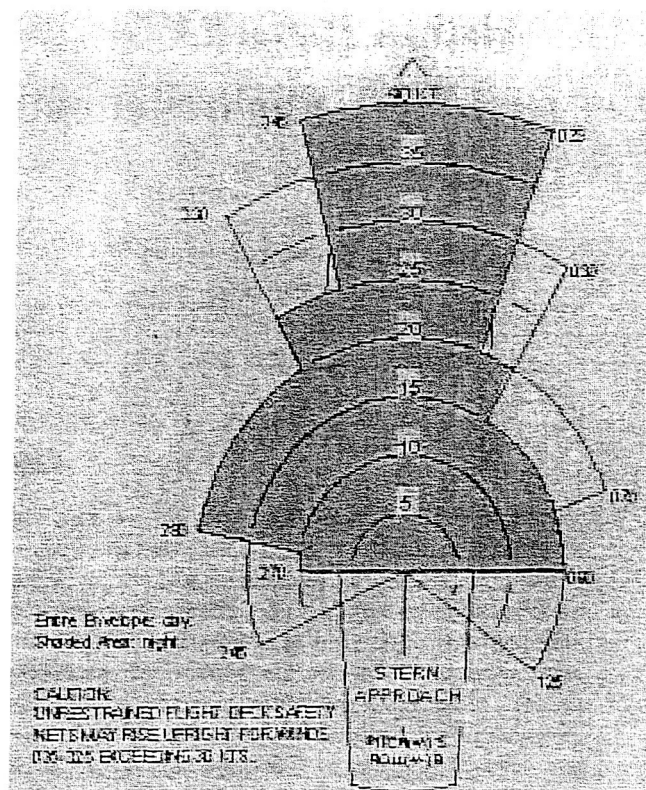


Figure 1. Shipboard rotorcraft operational envelope

New Sensor Technology

Recent advances in sensor technology such as Doppler lidar [9] and other techniques are leading to the development of aircraft-based sensors which can collect large amounts of airflow velocity data in real time. It is likely that aircraft-mounted hardware will soon be available that can reliably scan the area a few hundred feet ahead of the aircraft and sample air particle vector velocities at one-foot intervals or less [10]. With the development of such devices, onboard detection systems that can convey detailed information about airflow hazards to pilots in real time become a possibility. Such systems will require an interface that can concisely present large amounts of data to the pilot in a comprehensive manner in real time, yet not distract from the pilot's primary task of flying the aircraft.

Airflow Hazard Visualization

Initial Usability Study

In a preliminary usability study [11], we presented numerous visual representations of regions of hazardous airflow to pilots, while simulating the cockpit view of a helicopter's final approach to shipboard landing on a projection screen. Variables studied included shape, color, and animation of the hazard indicators.

Common techniques used by flight test engineers in understanding ship airwake usually include 3D motion, such as smoke trails injected into wind tunnels. Viewers of the video sequences often find the visualization of the air particles more instructive than static presentations [6]. However, upon being shown animated imagery over shipboard landing sites, the pilots in our preliminary study strongly rejected the use of dynamic indicators.

The pilots favored much simpler imagery than we had initially anticipated. Helicopter pilots landing on shipboard must focus all their attention to complete the landing safely, and have little spare cognition to analyze detailed quantitative information about hazards. An abundance of detail, motion (animation), complex shapes, and too many colors were all ruled out as distracting and possibly dangerous in the high-demand environment. The visual indicators had to be sufficiently translucent so as not to obscure any critical shipboard visual cues that the pilots needed as landing aids. The pilots desired to be informed only of the location of the hazard and its severity — a warning (yellow) or danger (red). In other words, our domain experts had informed us of the need for a decision support system with minimum critical information, not a scientific visualization system, and their reasons had to do with the division of attention in the high-demand environment.

This first phase of the study also revealed a strong preference by the pilots for a display in which the hazard indicator appears to be spatially conformal with the actual hazard in the physical scene. During potentially dangerous conditions, the pilot's attention will inevitably be focused outside the cockpit during the critical landing moments; he or she will not want to glance away and down at a cockpit instrument display. The pilots strongly favored an augmented-reality hazard visualization display on a head-up display (HUD). However, the display must be thoughtfully designed not to distract from the key shipboard visual cues, especially when these cues are degraded during a nighttime or poor-weather landing.

Earlier studies have demonstrated that head-up displays with superimposed symbology may occasionally cause performance problems due to attentional capture by the perceptual grouping of the superimposed symbols [12, 13]. "Scene-linked" head-up displays, or displays where there is no differential motion between the superimposed symbology and the outside scene, can solve this problem. Our study also confirmed the requirement for a head-up display where the hazard indicator is three-dimensional and appears to be physically part of the world.

The pilots stressed the importance of utilizing conventional symbology at all times. They emphasized the danger even a moment of confusion could cause, and strongly recommended that the symbology used in our

head-up display conform to current aviation standards. It was particularly important that our symbols not have any chance of being confounded with other types of HUD symbology already in use. The results from this prototype study enabled us to select a design that was substantially different from any existing type of HUD symbology.

Implementation of Flight Simulation Interface

With the knowledge gained from the results of the preliminary study, we implemented a version of our interface in Advanced Rotorcraft Technology's (ART) high-fidelity rotorcraft simulator [14], a fixed-base, aerodynamically accurate flight simulator with a three projection screen display (Figure 2). ART, located in Mountain View, California, is a rotorcraft flight simulation company specializing in non-linear dynamics modeling and analysis [14].

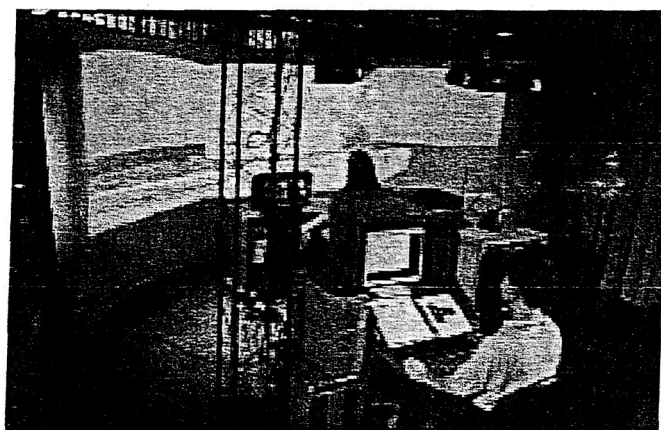


Figure 2. ART flight simulator with pilot in front of projection screen and operator at rear console

ART's visual subsystem is layered on top of OpenGVS [15], an OpenGL-based [16] scene manager built by Quantum3D. As a result, we could generate complex three-dimensional OpenFlight [17] objects in MultiGen software, import them into ART's flight simulator graphics subsystem, and manipulate them as desired in the flight simulator scene. OpenGL is an industry-standard API for developing 2D and 3D graphics applications. OpenFlight is a commercial, hierarchical 3D scene description file format, based on OpenGL.

Simulator Validation and Quality

ART's aerodynamic models have been verified by the US Navy via stability and control techniques and frequency domain validation [18, 19]; and Navy flight test engineers and pilots have stated that they are more aerodynamically accurate than other rotorcraft flight simulators currently available [18].

The only formal criteria to validate the performance of a high fidelity rotorcraft dynamic flight model are those in FAA Advisory Circular 120-63, Helicopter Simulator

Qualification [20]. ART's dynamic models do not fully meet the FAA Level D specifications, although they are very close in many flight regimes. However, these criteria are intended for training simulations (for example, the aircraft cockpit must be faithfully depicted) and are not as relevant for our purposes since we do not need to train helicopter pilots, but instead are looking for an aerodynamically accurate flight simulation. Additionally, the criteria are so difficult for rotorcraft simulators to meet (the error tolerance in measured rotorcraft data is often greater than the Level D specifications; for example, Level D requires that the torque error is within 3%, which also falls within the modern flight test measurement error range [18]), that there are no physics-based rotorcraft flight models available today that fully satisfy the FAA Level D requirements for rotorcraft [19].

Simulator Specifications

The study was performed in a high fidelity helicopter flight dynamics simulator with a single seat configuration, flight controls with force feedback, instrument panel, and a three-channel projection outside world visual system utilizing 3D Perception projectors to provide 1024 x 768 resolution at 1000 ANSI lumens. Visual rendering is done using ART software that supports rendering on OpenGL graphics cards using OpenFlight format visual databases. Image generation is done on PCs with graphic acceleration hardware that provides a 60 Hz update rate with full-screen anti-aliasing and a 188" horizontal by 54" vertical field of view on a 6.5-ft radius cylindrical screen.

An operator console provides full simulator control, monitoring of the visual system and instrumentation displays, initialization to saved reset points and arbitrary test conditions. Control loaders for the pilot's controls are electric and are driven by software that interfaces the flight dynamics model to the control loaders and edits the force feel characteristics. Four sets of control loaders are used to drive the longitudinal cyclic, lateral cyclic, collective and pedal controls. Computer generated images are rendered of the instrument panel. A dual 1.9GHz AMD processor computer with two graphics boards, located in the operator console, is used to drive a flat panel display that is mounted behind instrument panel overlays.

Flight Simulation Usability Study

Study Design and Implementation Process

We used a three-phase iterative design process in developing the interface and the study protocol. Highly detailed and realistic 3D models of a Sikorsky UH-60 Seahawk helicopter (Figure 3) and a Navy LHA (Tarawa-class) ship (Figure 4) had already been input into the flight simulator system. Additional details of the simulation study can be found in [21] and [22].



Figure 3. Sikorsky UH-60 Seahawk helicopter (US Govt. image, <http://www.arc.nasa.gov>)

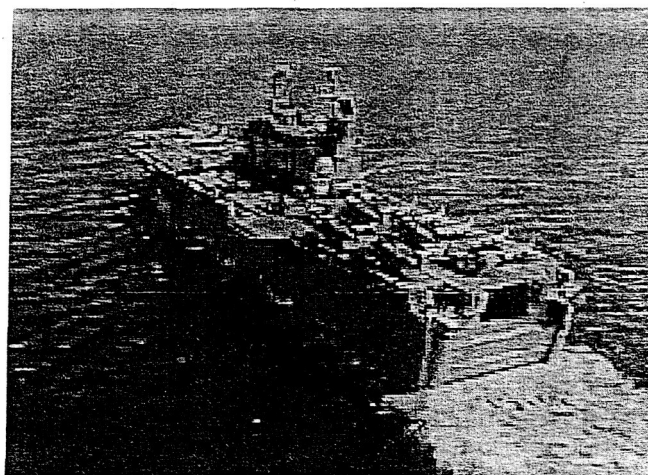


Figure 4. LHA steaming, loaded with aircraft (US Govt. image)

In the first phase, we reviewed US Navy Dynamic Interface (DI) helicopter-shipboard flight test data for the H-60 and LHA and selected four critical scenarios where, depending on the speed and direction of the wind over the ship deck, hazardous airflow could occur (Figure 5).

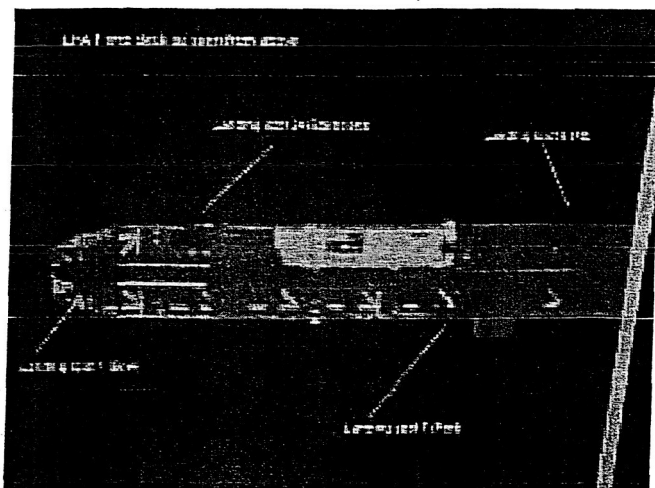


Figure 5. Photo from ART flight simulator, labeled: landing spots and hazard locations for the four scenarios on the LHA-1 ship

We defined a "scenario" as a combination of wind direction and approach to a landing spot (the LHA had ten different landing spots) where hazardous airflow could occur near or over the chosen landing spot (Table 1). In situations similar to these, accidents had occurred in the past.

Table 1. Flight Simulator Scenario Descriptions
Simulator Scenario Descriptions¹

Scenario	Approach Configuration	Landing Spot	Wind Direction	Wind Speed	Problem Description	Problem Location and Size	Expected Problem Manifestation
Starboard	S1	3A	060 degrees	Low	Upwelling over deck edge	Low Hover, near landing spot center	Outboard deck edge: High torque required = suckdown
	S2			Medium	downdraft inboard and outboard of deck edge		Deck edge: Low torque required/ballooning
	S3			High			Inboard deck edge: High torque required = suckdown
	S4			Extreme			
Aft	A1	9	360 degrees	Low	Elevated large scale turbulence intensity aft of island to aft edge of ship	Directly aft of island from deck up to above island height	Elevated control workload in all axes, esp tail rotor and lateral
	A2			Medium			
	A3			High			
	A4			Extreme			
Port	P1	7	300 degrees	Low	Longitudinal vortex inboard of deck edge at rotor height	Inboard of deck edge at low hover heights	Excessive lateral and directional control requirements; added turbulence with upwind aircraft
	P2			Medium			
	P3			High			
	P4			Extreme			
Bow	B1	1	360 degrees	Low	Strong downwash in recirculating bubble; upwash at fwd edge of bubble	Downwash aft of spot, upwash fwd of spot	Suckdown/added torque req'd aft of spot; Ballooning/lower torque req'd fwd of spot
	B2			Medium			
	B3			High			
	B4			Extreme			

Notes:

1. Ship, Course, Speed, Sea State, Temperature, Ship Motion, Gross Weight, Loading are identical for all scenarios. Ship Course is directly to North or 360 degrees.

We input actual airflow data from Navy DI flight tests, computational fluid dynamics (CFD) calculations, and wind tunnel tests into the simulator. We estimated wind

conditions that would create approaches with varying landing difficulties for each ship/wind-direction scenario. An experienced Navy helicopter test pilot flew all the stored approaches to verify the realism of the simulation, the location of the areas of hazardous airflow, and the validity of our landing difficulty ratings.

For the second phase, based on the test pilot's input and after lengthy examination of the airflow data, we created translucent 3D OpenFlight surfaces that outlined the volumetric regions of hazardous flow (Figure 6). (Actual surfaces were more translucent than pictured in the figure.) Based on the results from the study of the low-fidelity prototype, we had selected a simple, static design for the hazard indicators and used only two colors, yellow (caution) and red (danger). The shape and appearance of the indicators were chosen to indicate the physical location of the hazard without undue distraction and without duplicating any symbology used for other purposes, while the color meanings are conventional and widely accepted in the aviation world.

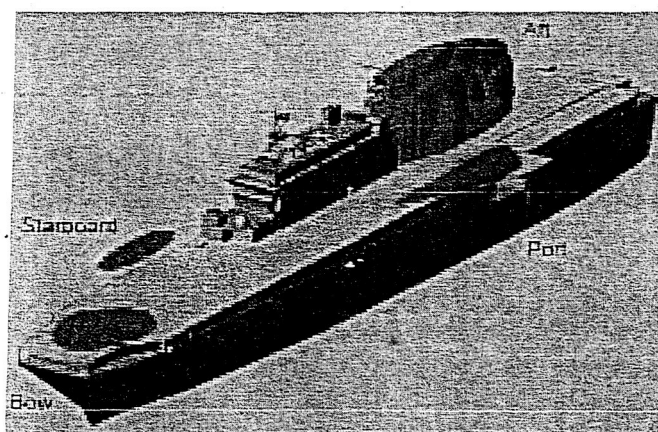


Figure 6. Visual hazard indicators used in the study for the four scenarios, Aft, Bow, Port, and Starboard (actual indicators were more translucent than depicted)

The objects were imported into the simulator's visual subsystem, scaling, rotating, and translating them into their proper positions on the LHA. This was done manually in order to accurately correlate the surfaces with the known areas of hazardous airflow from our study of the data. The objects were linked to the ship so that they seemed to be part of the simulated outside world; they appeared as clouds or curtains hovering over particular locations on shipboard. This is an accurate model of shipboard airwake; any hazardous areas produced by wind blowing over ship structures will move along with the ship.

The following figures (Figure 7)(Figure 8)(Figure 9)(Figure 10) are digital photos taken in the simulator room at Advanced Rotorcraft Technology, Inc. (ART) that depict the visual appearance of each of the four hazard indicators for each of the Aft, Bow, Port, and Starboard scenarios.

The yellow (caution) indicators are shown; the red (danger) indicators were identical except for their color.



Figure 7. Hazard indicator (yellow, caution) - Aft scenario

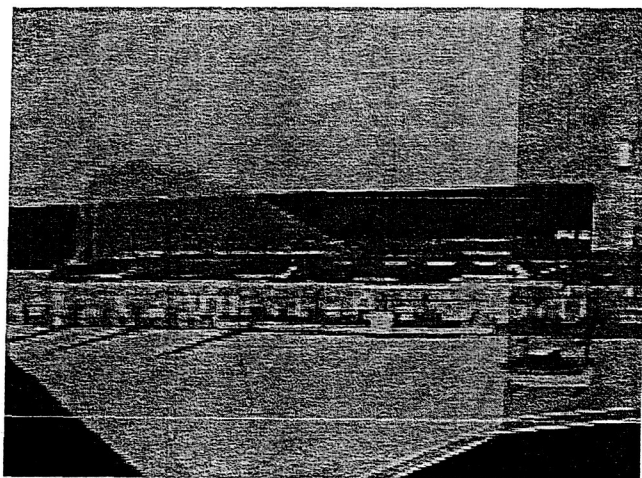


Figure 8. Hazard indicator (yellow, caution) - Bow scenario

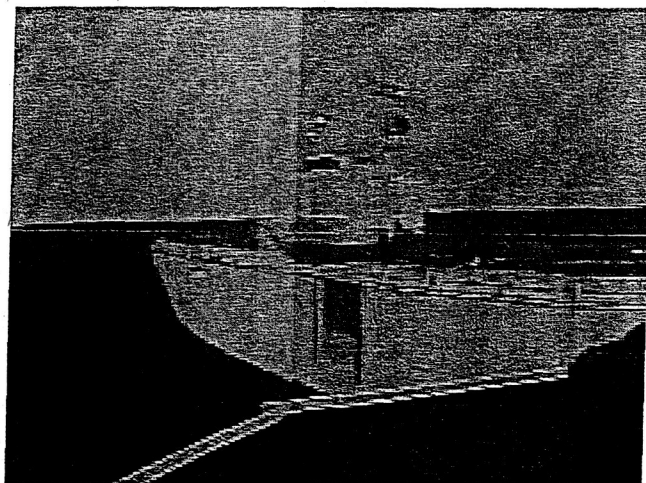


Figure 9. Hazard indicator (yellow, caution) - Port scenario

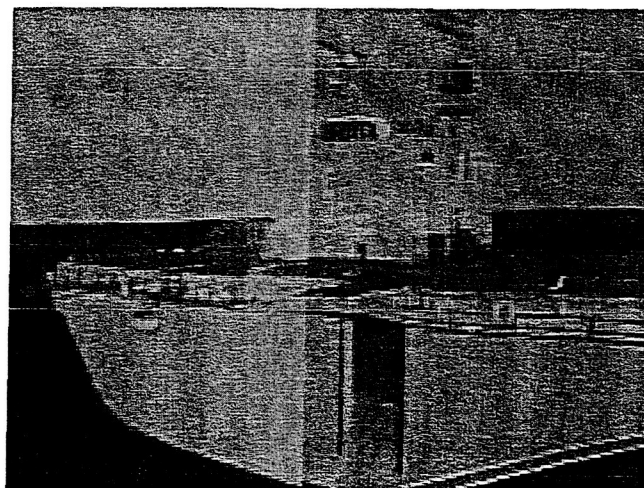


Figure 10. Hazard indicator (yellow, caution) - Starboard scenario

Finally, an experienced Navy test pilot flew all the approaches and performed a final verification of the correct placement of the hazard indicators as well as the validity of the stated difficulty levels of the approach.

At this point, we were confident that we had a set of realistic, aerodynamically accurate approaches for helicopter pilots landing on an LHA ship. We checkpointed all 28 different approaches, plus four practice approaches with light winds for the orientation flight, over four scenarios in preparation for our flight simulation usability study.

Study Protocol and Design

The study was a 3 (landing difficulty) x 2 (presence or absence of visual hazard indicator) x 4 (approach type) + 1 x 1 x 4 (control) within-subjects design. Each pilot flew the same 28 simulated approaches, but in different orders.

Each participant received a pre-flight briefing that explained the structure of the simulation and the use of the controls of the simulator and instructions as to the meaning of the yellow and red hazard indicators. Participants then performed a series of orientation flights before beginning the actual test. There were five orientation flight sequences. First, pilots were given a few minutes to accustom themselves to the "feel" of the simulator by flying the simulated helicopter from a low speed up to cruise and back down to a hover, and then flying around the ship and simulated terrain. Then the pilot flew four approaches, one to each of the four targeted landing spots for the test scenarios, but with low (non-hazardous) winds. Thus they were familiarized with the environment and the out-the-cockpit view for each of the approach scenarios.

The dual purposes of the orientation flights were to accustom them to the feel of the controls of the simulator, and to determine if they had the skill level to be a credible participant in the experiment. Out of 17 pilots recruited for the study, one was unable to fly the orientation flights and was excused, leaving 16 pilots who then completed the test approaches.

At the outset of each approach, pilots were given wind direction but not wind speed. Revealing wind speed could introduce bias due to the pilots' assumption that wind speed correlates with landing difficulty level, although pilots were briefed that hazards could occur even at low wind speeds.

Participants

We recruited 17 military and civilian helicopter pilots by word-of-mouth and through emailed requests for volunteers. 16 pilots (1 female) flew the orientation flights successfully and completed the simulation test. This group of pilots had no previous experience on the simulator used in the experiment and had not seen or heard of any type of visual hazard indicating system before. Pilot experience ranged from 200 to 7300 helicopter flight hours with the median number of hours being 2250, from 2 to 46 years of experience as a helicopter pilot with the median 13 years, and were from 25 to 65 years old, with a median age of 36 (Table 2). All pilots had normal or corrected-to-normal eyesight and were not color-blind. The study took about two hours, of which about one hour was spent in the simulator, and pilots were not paid for their participation.

Table 2. Pilot Demographics

Pilot	Employer	Helicopter Hours	Age	Years of Experience	Number of Shipboard Landings
1	Coast Guard	800	30	3	40
2	Coast Guard	1500	28	5.5	60
3	Coast Guard	770	26	2.5	200
4	Coast Guard	420	26	2	30
5	Coast Guard	200	25	2	75
6	Coast Guard	5600	43	22	1000
7	NASA	3100	59	46	100
8	Air Force/Air National Guard	3000	37	18	18
9	Air Force/Air National Guard	1800	34	8	0
10	NASA	2500	65	35	302
11	Army, civilian	4300	56	34	6
12	Air Force/Air National Guard	2000	33	7	0
13	Army, NASA	7300	51	29	150
14	Air Force, NASA	4000	60	36	0
15	Navy, Marines	3200	41	18	1500
16	Marines	850	33	8	600

Approach Description

For each approach or run, the simulator was set to a previously saved checkpoint that positioned the helicopter at 250 feet above mean sea level and 2600 feet back of the stern of the ship. Wind and turbulence conditions that would produce a landing of difficulty 1-4 had been previously programmed into the simulator, and the appropriate hazard indicators were turned on at the beginning of the approach (if an indicator was supposed to be present). The simulator flight controls were trimmed to a 30-knot airspeed, and the pilots were given a verbal clearance to land on one of four landing spots and the wind direction. The pilots were asked if they were ready, and then the simulator was set running. Pilots flew until the landing was complete, they verbally called out an aborted approach, or they crashed. Then the simulator was stopped and set up for the next run. Pilots were encouraged to make verbal comments during the test, and the entire test was videotaped for all pilots. The video camera was positioned behind the pilot, facing the projection screens, so that the pilot would not be visible on the tape.

Approach Scenarios

Scenarios were labeled based on which landing spot the pilot would be cleared for and where the airflow hazard would occur under certain wind conditions.

Scenario A ("Aft"): Direct stern approach to landing spot 9, the aft-most landing spot on the LHA. With a direct bow wind, and at high wind speed and turbulence levels, an airflow hazard would occur downwind of the ship superstructure over landing spot 9.

Scenario B ("Bow"): A 45-degree approach to the most forward spot on the bow of the ship, spot 1, and winds directly from the bow. This created an area of heavy downdraft ("suckdown") directly over spot 1, which was often unexpected as it occurred even at relatively low winds and even in smooth wind conditions.

Scenario P ("Port"): A 45-degree approach to the port side of the ship, to landing spot 7, just forward of the elevator and next to the ship superstructure. Winds from 300 degrees (assuming the ship is moving toward the north or 360 degrees) caused a rotor to form over the deck edge just over landing spot 7. Again, this hazard formed even at relatively low winds.

Scenario S ("Starboard"): A 45-degree approach from starboard to landing spot 3A just forward of the ship superstructure. When winds are from 60 degrees, a vortex forms just at the deck edge and beside landing spot 3A.

Landing Difficulty Level

We used four different landing difficulty levels (Table 3) based on the Navy's Pilot Rating Scale of landing difficulty [7]. Each pilot flew each approach scenario at all landing difficulty levels. For each of LD 2 through 4, each pilot flew one approach with and one without a visual hazard indicator. For LD 1, each pilot flew one approach without a hazard indicator. Thus, each pilot flew 7 approaches in each of the 4 landing scenarios, a total of 28 approaches per pilot. The approaches were designed to take about 1-2 minutes each; therefore, the entire simulation took about one hour per pilot; this time length was designed to prevent pilot fatigue.

Table 3. Landing Difficulty Levels

Landing Difficulty	Definition	Approaches per pilot	Purpose
LD 1	No problems; minimal pilot effort required	4 w/o indicator	Control
LD 2	Moderate effort required; most pilots able to make a safe landing consistent with some effort	4 w/o indicator + 4 with indicator	Test negative effects of hazard indicator
LD 3	Maximum pilot effort required; repeated safe landings may not be possible	4 w/o indicator + 4 with indicator	Test benefit of hazard indicator
LD 4	Controllability in question; safe landings not probable under these conditions	4 w/o indicator + 4 with indicator	Test benefit of hazard indicator with pilot instructional procedure

Landing difficulty 1 (LD 1) – Control: These approaches showed how well the pilot could operate the simulator in the absence of particular hazards, and also provided periods of rest to the pilots to reduce fatigue and avoid discouragement (since the test consisted of an abnormally high percentage of very challenging landing conditions).

Landing difficulty 2 (LD 2): Testing for negative effects of the hazard indicator. This difficulty level required moderate pilot effort. The hazard indicator (if present) was a translucent yellow object outlining the area where turbulent flow could be found. Because the conditions at LD 2 are considered to be within normal pilot abilities, we would expect few crashes even without the hazard indicator. The hypothesis tested at LD 2 was that the hazard indicator would not increase the crash rate (e.g. by distracting the pilot). Pilots were instructed that the yellow hazard represented caution and that they could continue the approach.

Landing difficulty 3 (LD 3): Testing for benefit of hazard indicator. This difficulty level required maximum pilot effort. The hazard indicator was the same type as for the LD 2 approaches. Pilots were told that yellow represented caution and they were to continue the approach. A higher crash rate was expected at LD 3 commensurate with the more challenging conditions compared with LD 2. We hypothesized that the hazard

indicator would reduce this crash rate – ideally, to a rate comparable to LD 2.

Landing difficulty 4 (LD 4): Testing for benefit of hazard indicator with pilot instructional procedure. At LD 4, safe landings were not probable. Fifteen pilots were told that if they detected a red hazard indicator along their approach path, standard operating procedure (SOP) was to abort the landing immediately. (The sixteenth pilot, who was not initially given this instruction, spontaneously proposed that it should be standard operating procedure.) These approaches test whether the same hazard indication methodology used for reducing the crash rate in marginal conditions will also operate reasonably in extreme conditions.

Order of Presentation

To compensate for possible learning effects, half the pilots flew scenarios A and P without the hazard indicators and scenarios B and S with the hazard indicators during the first half of the test, and then conversely for the second half. The other pilots flew scenarios A and P with hazard indicators and scenarios B and S without indicators during the first half of the test. This was accomplished by defining an approach order randomly within these constraints, then reversing it to create a second order, then switching the first and second halves to create a third and fourth order. It was arranged that the most difficult approaches would not all follow one another, to reduce the likelihood of pilot fatigue.

Dependent Variables

During the simulation, 50 variables, such as velocity and position of aircraft in x, y, z, control stick position both lateral and longitudinal, collective and pedal positions, landing gear forces, etc., were collected by the flight simulator at 10 Hz and stored in data files labeled for each run and pilot. From these data, we computed the crash rate. A "crash" was defined as an impact with the ship's deck with a vertical velocity of 12 feet per second (fps) or greater as measured by the simulator. (This value is based on the US Navy standard structural limitation for helicopters. In order to be certified for shipboard use in the US Navy, rotorcraft must be able to withstand an impact of 12 fps upon touchdown [23, 24].)

We also gathered subjective pilot opinions from a 21-probe Likert-scale (1-5) questionnaire administered to the pilots at the end of the simulation. For each probe, the pilots had to circle one of "Strongly Disagree" (1), "Disagree" (2), "Neither Agree Nor Disagree" (3), "Agree" (4), and "Strongly Agree" (5).

Hypotheses

We tested five hypotheses:

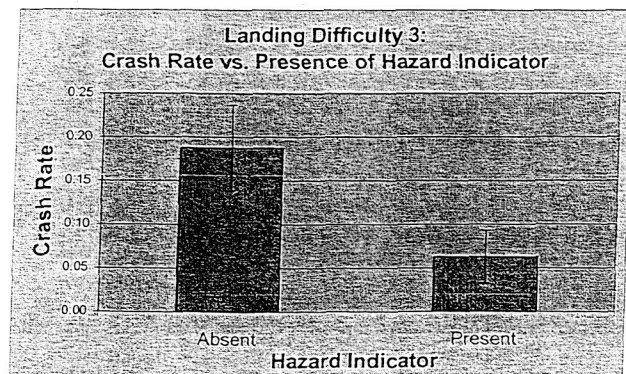
1. Crash rate will be reduced by the presence of hazard indicator (LD 3).
2. Crashes will be eliminated by red hazard indicator if a standard operating procedure (SOP) is given to the pilots (LD 4).
3. Hazard indicator will not cause distraction or degradation in performance in situations where adequate performance is expected without indicator (LD 2).
4. Pilots will say they would use airflow hazard visualization system.
5. Pilot workload (as measured by frequency of control travel oscillation) will be reduced in the presence of the hazard indicator.

Results

In this section, we present the analysis of crash rate data, other flight statistics and subjective data, and illustrate the analysis with relevant pilot comments. Our hypotheses were generally confirmed by the data. Pilot feedback was as a rule favorable to the system, and, additionally, indicated directions for further study.

Hypothesis 1 confirmed. For the test at landing difficulty 3, there were 12 crashes out of 64 approaches without the hazard indicator (crash rate .19, standard error .049) and 4 crashes out of 64 with the hazard indicator (crash rate .063, standard error .030) (Table 4). A t-test for paired samples shows that the hypothesis that the presence of the hazard indicator reduces the frequency of crashes during simulated shipboard helicopter landings is confirmed ($t=2.39$, $df=63$, $p<0.00985$).

Table 4. Landing Difficulty 3 - Crash Data



These strong results indicate the system should improve helicopter flight safety under hazardous conditions.

During the tests, pilots remarked several times that the indicators were helpful warnings; that they were able to modify their flight path or power settings to counteract the known hazardous conditions, or make appropriate safety decisions based on knowledge gained from viewing the hazard indicators. Additionally, in the approaches without hazard indicators, pilots commented on several occasions that they were surprised by the wind conditions as they entered the hazardous areas, even though they had usually deduced that conditions were extreme before they entered the hazard zones. In a few of these runs where the pilot made such a comment, the approach terminated in a crash.

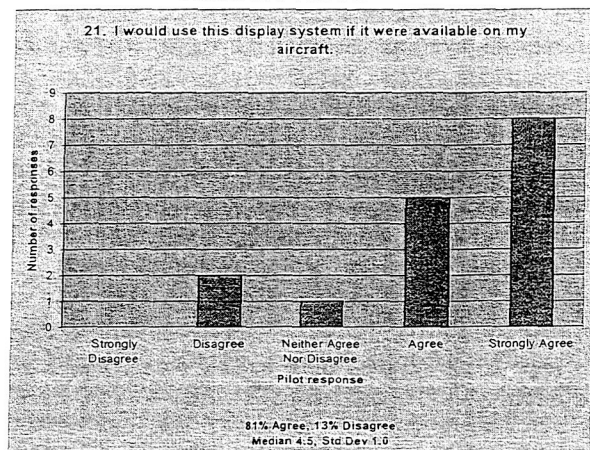
Hypothesis 2 confirmed. At landing difficulty 4 (beyond the capacity of the aircraft), there were 0 crashes in 64 approaches with the hazard indicator as opposed to 15 crashes out of 64 without the indicator, for crash rates of 0% and 23% respectively. (Standard errors were 0 and .053.) A t-test for paired samples shows that this hypothesis—that the presence of the red hazard indicator combined with appropriate instructions to the pilot prevents crashes—is strongly confirmed ($t=4.39$, $df=63$, $p<0.00022$). What this means is that although pilots may sometimes continue into a situation that is beyond the capacity of the aircraft if they do not have sufficient knowledge of the danger of the situation, giving them the appropriate information in a clear and simple manner during the approach can prevent accidents. This is an improvement over the current envelope system because, as one pilot noted, it would be very helpful in case the winds shifted during the approach. If he suddenly saw a red hazard area appear on deck, he would know immediately to abort the approach.

Hypothesis 3. No negative effect of hazard indicator. It appears that the hazard indicators did not distract the pilots. The crash rate at LD 2 was the same with and without the indicator. Crash rate for both was identical, 7.8% or 5 crashes out of 64 for each set of approaches. (Standard error was .034.) However, because the crash rate was low, with a sample of this size it is not possible to conclusively state that the hazard indicator made no difference in crash rate. On the other hand, the pilots did not feel the hazard indicators were distracting. On our simulation evaluation questionnaire, probe 6 was, "The airflow hazard visualization distracted me from the task of flying the aircraft." The pilots disagreed with this statement: 94% of the pilots answered "Strongly Disagree" (1) or "Disagree" (2) with the median "Disagree" (2).

Hypothesis 4 confirmed. When pilots were asked to report their level of agreement with the statement, "I would use this system if it were available on my aircraft," eight pilots chose "Strongly Agree" (5), five chose "Agree" (4), one chose "Neither Agree Nor Disagree" (3) and two chose "Disagree" (2). Median response was 4.5, between "Strongly Agree" and "Agree" (Table 5). This indicates

confirmation of Hypothesis 4, that pilots would use the system.

Table 5. Probe 21 Results



Hypothesis 5. Previous work has indicated that rotorcraft pilot workload may be estimated by frequency of control oscillation, specifically lateral cyclic movements [5]. We applied Fourier analysis to the time-series data of lateral cyclic position (XA) obtained from the simulator, initially with specific emphasis on those runs which terminated in a crash.

The following graph (Table 6) illustrates those results for one pilot during three different approaches to the landing spot aft of the island: a control run at landing difficulty 1, a run at landing difficulty 3 without the hazard indicator, and a run at landing difficulty 3 with the indicator. The run at LD 3 with no hazard indicator terminated in a crash; the other two were completed with a successful touchdown. We applied the Fourier transform to the last 25.6 seconds of each of the time series landing runs, since the final critical seconds before touchdown are the most indicative of maximum pilot workload. The spectrum was analyzed in a range of frequencies around 1 Hz, where control movements can be presumed to be intentional (rather than, say, due to aircraft vibration). Low frequency movements (at approximately 0.5 Hz and below) are indicative of normal control travel, whereas previous work has suggested that frequency peaks near 1 Hz indicate a dangerously overloaded pilot [5].

Table 6. Typical lateral cyclic power spectrum, last 25.6 seconds of approach to landing spot aft of island

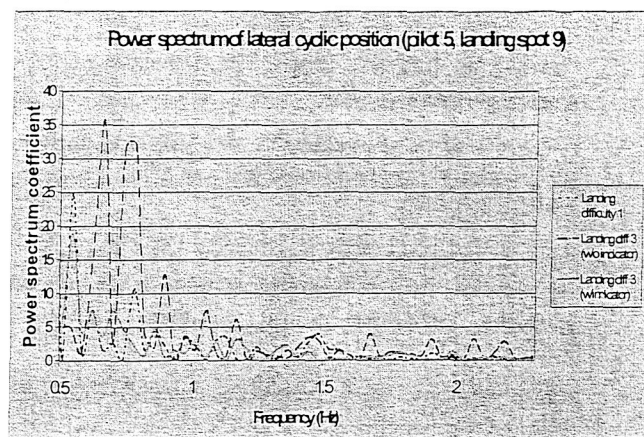


Table 6 shows the Fourier power spectrum for XA, the lateral cyclic position. The Fourier power coefficients P_i in the plot are obtained as the squared magnitudes of the complex-valued Fourier amplitudes,

$$P_i = |X_i|^2 = \text{Re}(X_i(XA))^2 + \text{Im}(X_i(XA))^2$$

where X_i is the i -th component of the Fourier transform of the XA time series.

For the run at LD 3 with no indicator, stronger peaks occur at higher frequencies than the other two runs. Peaks at approximately .6, .7, and .9 Hz are visible, with lesser peaks at 1.1 and 1.2 Hz; there are no corresponding frequency peaks for the other two runs. The total spectral energy in this range near 1 Hz is about twice as great in the run at LD 3 without a hazard indicator, as compared to the run with a hazard indicator or the control run at LD 1. Data analysis is ongoing in this area, but this preliminary analysis of lateral cyclic travel appears to point to a reduction in pilot workload with the presence of the hazard visualization system.

Control group (LD 1). Because conditions in the simulator are somewhat different than in a real helicopter, and visual and proprioceptive feedback is reduced (no chin bubble through which helicopter pilots can look down past their feet and see how close they are to the deck, no depth perception in the visuals, no bump when the landing gear contacts the deck, etc.), and especially because pilots are flying it for the first time without any training with an instructor (the usual procedure when transitioning to a new aircraft), a certain number of crashes in the simulator are to be expected. For this reason we included a set of low-hazard approaches in the study to serve as a control (LD 1).

The crash rate at landing difficulty 1 was 9.4% (6 out of 64, standard error .037), which is not significantly different from LD 2 or LD 3's crash rates (5 out of 64, std. err. .034 and 4 out of 64, std. err. .030, respectively; t-test, $p=0.38$).

and $p=0.26$) when the hazard indicator is present. In other words, the use of the hazard visualization system reduced the crash rate to the same level as that of the control approaches.

Summary of Crash Statistics

This subsection describes the overall crash statistics for our experiment, where, as explained earlier, a “crash” was defined as an impact with the ship’s deck of more than 12 feet per second. (Table 7) summarizes all the data, and the following sections describe further statistical analysis of the data and our interpretations.

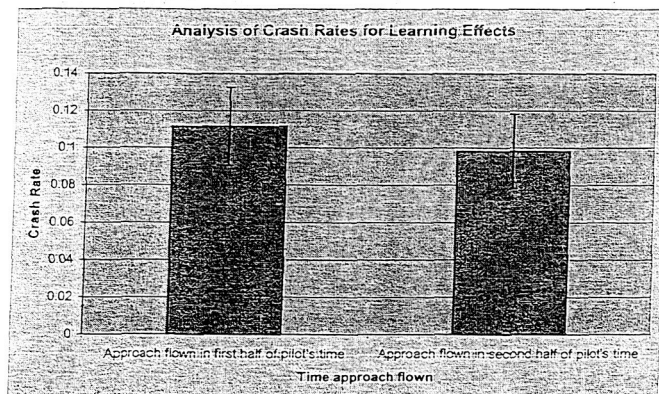
Table 7. Crash Statistics for All Landing Difficulties

Landing Difficulty	Hazard Indicator	Crashes	Total Approaches	Crash Rate	Standard Error
LD 1	No	6	64	0.0938	0.0367
LD 2	No	5	64	0.0781	0.0338
	Yellow	5	64	0.0781	0.0338
LD 3	No	12	64	0.188	0.0492
	Yellow	4	64	0.0625	0.0305
LD 4	No	15	64	0.234	0.0534
	Red	0	64	0	0

Learning effects

For the first half of the simulator test, the pilots crashed 25 times out of 224 approaches flown for a crash rate of 11.2%, while in the second half of their tests, the pilots crashed 22 times out of 224 approaches, for a crash rate of 9.8% (Table 8).

Table 8. No apparent learning effects in study

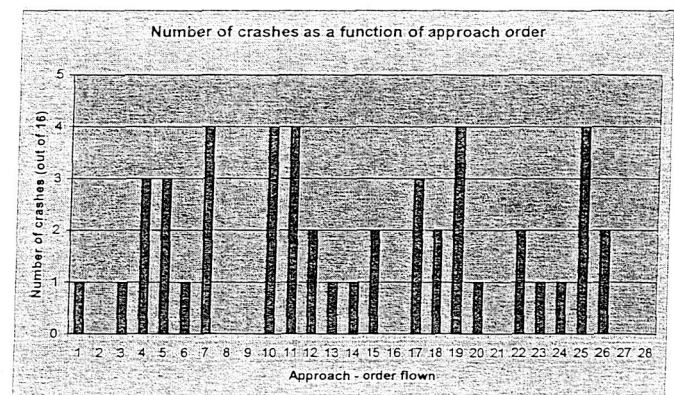


This is not a significant difference (t-test, $t=0.46$, $df=445$, $p=0.32$), although the pilots did state that they believed they performed better as they flew the simulator longer. (Probe 17: “It became easier over time to fly because my experience on the simulator increased.” Eight

pilots answered “Strongly Agree” (5), six pilots chose “Agree” (4), and two pilots chose “Neither Agree or Disagree” (3). Median response was 4.5.) This appears to indicate that learning effects did not bias our study, as was intended in its construction.

We considered whether there could be other reasons for this result. For example, a few of the pilots commented toward the end of the 28 approaches that they were getting tired. It is possible that there were more crashes at the beginning of the flights, but this effect was masked by more crashes at the very end of each pilot’s simulator time. In order to test this theory, we graphed crashes as a function of approach order (Table 9). In this graph, the x-axis lists the order flown, from 1 to 28, and the y-axis lists the number of crashes at that point (out of 16 approaches flown). The graph makes evident that there is no such pattern of bias in the number of crashes as a function of approach order. Therefore, we concluded that learning effects did not bias our study.

Table 9. No evidence for learning effects or other global effects as a function of order flown



Waveoff Rate Analysis

In order to address the concern that the hazard indicators may simply make a pilot more cautious, and that the reduction in crash rate was solely due to an increase in aborted landings, we also analyzed the overall waveoff rates. A waveoff is an aborted landing, or “go-around,” where the pilot decides a safe landing is not probable, and proceeds to climb to re-enter the pattern and (possibly) attempt the landing again. In our experiment, as soon as the pilot called for an aborted landing, we terminated the run, and the pilot did not attempt another landing under those conditions.

In reality, were a pilot to wave off, the next step would most likely be another landing approach, perhaps calling for the ship to turn further into the wind, or perhaps

requesting a different landing spot. However, for the purposes of our simulation, we counted waveoffs separately from completed landings. Each approach, therefore, took one of three possible terminations: a completed landing, a waveoff, or a crash. Because go-arounds are a frequent and necessary part of safe flying, for our main analysis above we considered the crash rate as our primary dependent variable in determining whether or not our system had a positive effect on flight safety under the stated conditions.

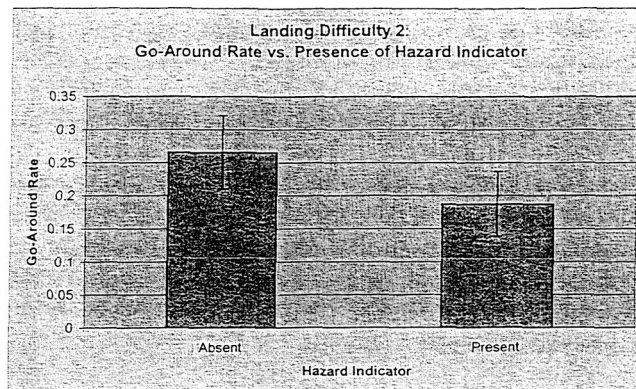
Many flight instructors believe that students should be taught that all landing approaches should really be considered approaches to go around. Any number of go-arounds are better than making a destabilized approach to landing that could end in a crash. Because this attitude is common in the aviation community, an increased number of go-arounds would not be considered a negative result. However, it can be supposed that there are operational considerations in naval aviation whereby a waveoff is costly in some sense (although it preserves the aircraft and pilot). Therefore, a hazard indication system that does not increase waveoffs would be (other factors equal) preferable to one that does. Waveoff data is summarized in (Table 10).

Table 10. Go-Around Statistics for All Landing Difficulties

Landing Difficulty	Hazard Indicator	Go-Arounds	Total Approaches	Go-Around Rate	Standard Error
LD 1	No	3	64	0.0469	0.0266
LD 2	No	17	64	0.266	0.0556
	Yellow	12	64	0.188	0.0492
LD 3	No	22	64	0.344	0.0598
	Yellow	23	64	0.359	0.0605

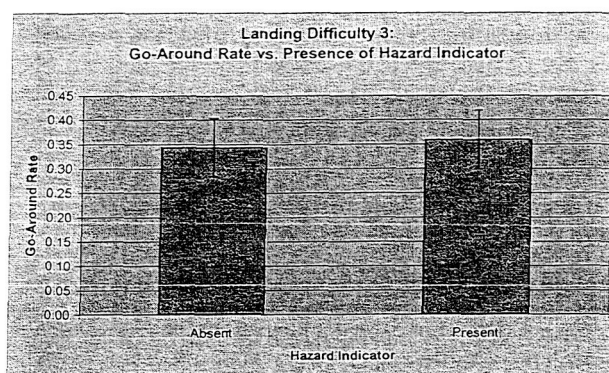
The waveoff rate at landing difficulty 2 with no hazard indicator was 17 out of 64 approaches (a rate of 0.266 with a standard error of 0.0556) and 12 out of 64 (a rate of 0.188 with a standard error of 0.0492) with the hazard indicator present (Table 11). This is not a significant difference ($t=1.04$, $df=63$, $p=0.15$) for landing difficulty 2.

Table 11. Landing Difficulty 2 - Go-Around Data



At landing difficulty 3, the waveoff rate when the hazard indicator was absent was 22 out of 64 (a rate of 0.344 with a standard error of 0.0598), almost identical to the rate when the hazard indicator was visible, 23 out of 64 (a rate of 0.359 with a standard error of 0.0604), again, not a significant difference ($t=0.18$, $df=63$, $p=0.427$) (Table 12).

Table 12. Landing Difficulty 3 - Go-Around Data



For cases where the ANOVA statistical test is applicable, it is a more conservative test of significance than individual t-tests. For the waveoff data, a two-way ANOVA on landing difficulty (2, 3) and hazard indicator (present, absent) shows neither a significant difference due to either factor alone, nor a significant interaction between the factors ($F_{crit} = 6.7$; for landing difficulty $F = 4.9$, $p=0.028$; for hazard $F = 0.31$, $p=0.58$; for the interaction $F = 0.69$, $p=0.41$).

We did not analyze the data for landing difficulty 4 because we instructed fifteen of the sixteen subjects to wave off whenever they detected a red hazard indicator in

their path, so any results from landing difficulty 4 would be artificial.

It appears, therefore, that the presence or absence of the hazard indicator at landing difficulties 2 and 3 does not affect the waveoff rate. Thus, analyzing the waveoff data does not lead to any changes in our conclusions about the four hypotheses described above.

Analysis by Pilot Experience Level

An interesting question was whether pilot experience level had any effect on performance, and on the effectiveness of the hazard indicators. In order to look at this question, we divided the 16 pilots into three groups, where there were natural gaps in their experience levels: less experienced, moderately experienced, and highly experienced (Table 13).

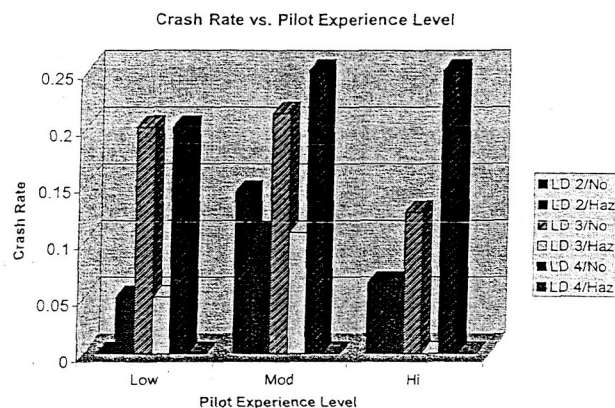
Table 13. Pilots grouped by experience level

Pilot Experience Level	Helicopter Flight Hours	Number of Pilots in Group
Less experienced	200 - 850	5
Moderately experienced	1500 - 3200	7
Highly experienced	4000 - 7300	4

One of the very experienced pilots had commented that he did not learn anything new from the placement of the hazard indicators, but he felt it might be a good training aid for more inexperienced pilots. Additionally, most of the less experienced pilots stated that they did learn something from the hazard indicators.

We therefore examined the data for evidence that the decrease in crash rates was concentrated among the pilots with less experience. The reduction, however, was seen across all experience levels, although we could not obtain statistical significance in most cases due to the lower sample numbers. The data is summarized below (Table 14).

Table 14. No significant difference between pilot groups based on experience level



In other words, the trends suggest that our hypotheses 1, 2 and 3 are true for the group of highly experienced pilots as well.

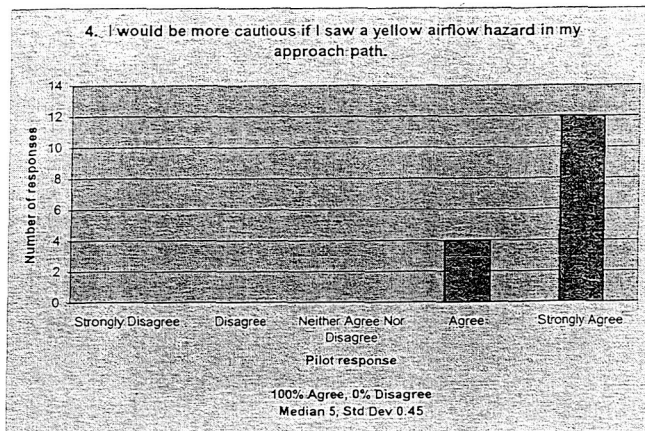
Analysis of Subjective Data from Pilot Evaluations

All pilots filled out a 21-probe Likert-scale post-simulation evaluation. The possible responses were (1) Strongly Disagree, (2) Disagree, (3) Neither Agree Nor Disagree, (4) Agree, or (5) Strongly Agree. In this section, we present the results of some of the probes other than those previously discussed in this chapter.

Probe 4. I would be more cautious if I saw a yellow airflow hazard in my approach path.

As (Table 15) illustrates, pilots exhibited caution upon viewing yellow hazard indicators. Several pilots commented that they changed their flight paths based on the location of the hazard indicators. We conjecture that this pilot action contributed to the lower crash rates at landing difficulty 3 when the yellow hazard indicators were present. One pilot did warn of the possibility that the hazard indicator could make pilots overcautious; however, the waveoff data did not seem to bear this out (there was no increase in waveoffs with the presence of a yellow hazard indicator).

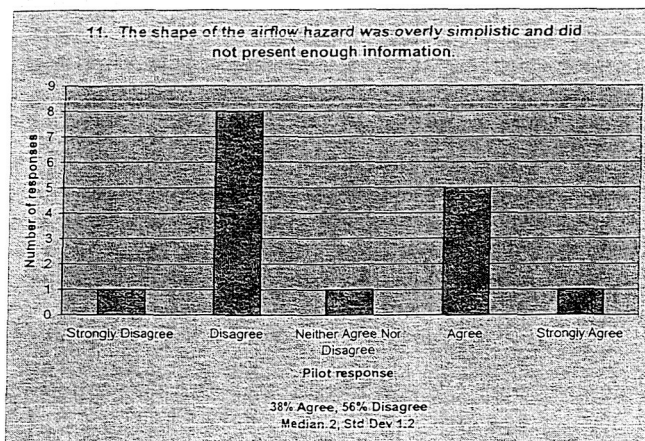
Table 15. Probe 4 Results



Probe 11. The shape of the airflow hazard was overly simplistic and did not present enough information.

Most of the pilots disagreed with this statement (Table 16). However, the bimodal distribution of responses coincides with pilot post-simulation commentary: it seemed that the pilots fell into two groups, one that wanted more information on the indicators, perhaps even some animation, and another that felt "the simpler, the better." A few pilots commented that they wanted a quantitative value for airflow speed as well as the qualitative indication of whether the hazard was beyond aircraft limits.

Table 16. Probe 11 Results

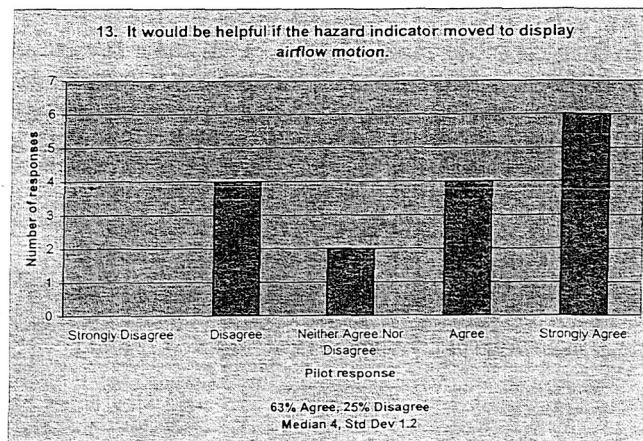


Probe 13. It would be helpful if the hazard indicator moved to display airflow motion.

(Table 17) illustrates the spread of opinions on indicator motion. Although the pilots were not as negative about motion or animation in this study as they were in the

low-fidelity prototype, in this study we did not show them any moving indicators. The strong, almost visceral reaction of the pilots in the earlier study always occurred as they were viewing an animated indicator on the screen. Additionally, when a few of the pilots who agreed with this probe statement were queried as to the type of motion, they concurred that the animation should not be too rapid, and all of them wanted the ability to stop the animation, especially close to the end of the approach.

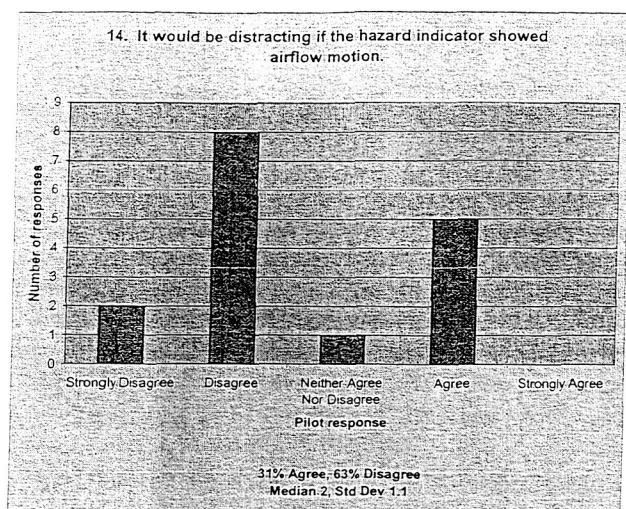
Table 17. Probe 13 Results



Probe 14. It would be distracting if the hazard indicator showed airflow motion.

Although the pilots mostly disagreed with this statement (Table 18), it must be noted that they were attempting to evaluate a hypothetical feature, and had not been given a chance to observe an indicator in motion. When the pilots who wanted airflow motion were asked for a reason, many stated that they wanted more information about the hazard at the beginning of the approach. Just as with probe 13, they concurred that they wanted to be able to turn off any motion.

Table 18. Probe 14 Results

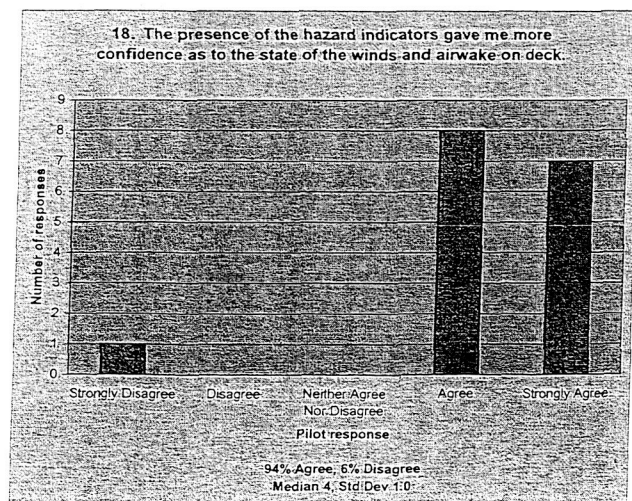


Probes 13 and 14 together indicate a need for further study on the use of animated indicators, as the benefits evidently anticipated by the pilots in the simulation study do not jibe with the strong aversion expressed by pilots in the low-fidelity prototype study.

Probe 18. *The presence of the hazard indicators gave me more confidence as to the state of the winds and airwake on deck.*

The pilots were almost unanimously in agreement with this statement (Table 19). The only pilot who disagreed was one of the most experienced pilots in our group, who stated that he already knew where all the hazardous areas were. We discuss this pilot's opinions further in the final section on pilot comments and suggestions.

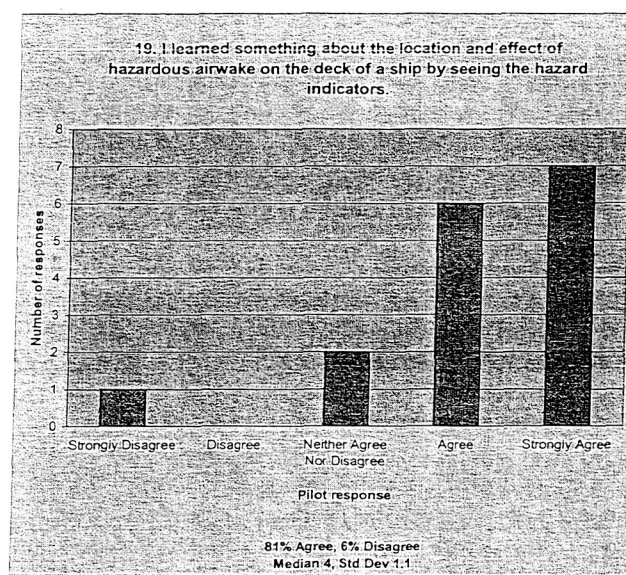
Table 19. Probe 18 Results



Probe 19. *I learned something about the location and effect of hazardous airwake on the deck of a ship by seeing the hazard indicators.*

Again, the pilots agreed with this statement (Table 20). The same experienced pilot that disagreed with probe 18 disagreed here; he said he already knew all about the location of hazardous airwake on ships. Indeed, he was one of the few pilots who did not crash at all during the simulation. The two who were neutral on this question were also relatively experienced.

Table 20. Probe 19 Results



Probe 21. *I would use this display system if it were available on my aircraft.*

We have previously discussed this result (see Table 5) as it directly relates to our Hypothesis 4. Overall, the fact that 81% of the participating pilots said they would use the system is a strong indication that such a system would meet with pilot acceptance if it were implemented and installed in aircraft. Combined with the strong positive results in pilot performance in the simulation study, it is evident that further research into the implementation of an in-cockpit airflow hazard display system is called for.

Pilot comments and suggestions

At the end of our questionnaire, probe 22 was an open-ended request for comments. We also gathered verbal commentary and suggestions from the pilots during the post-flight debrief. Several pilots commented extensively.

In this section, we give some of their responses and suggestions.

As discussed earlier, there appeared to be a bimodal distribution of pilot opinions on whether the indicators were overly simplistic and needed to provide more information, or that more information would be distracting. We present quotes from two pilots who illustrate the opposing viewpoints:

One of the most experienced pilots in our study (who, however, did not have any helicopter shipboard landings) commented, "Interesting concept – needs some better depiction of what the hazard really is, i.e. vortex, rooster tail. Some velocity information would give the pilot some valuable lead information to anticipate what to do."

On the other hand, a pilot with a moderate amount of experience but with many helicopter shipboard landings, said, "with all you have to do, landing... controlling your decel[eration]... especially at night... you don't want any distraction" in the form of animation or numeric indications in the hazard visualization.

These comments indicate that further studies are called for, where different types of hazard indicators, some with an indication of airflow motion, some animated, some with numeric readouts, are compared.

Another area for further research lies in making the display adaptive. Several pilots commented that they wanted more detail at the beginning of the approach and less at the end. To that end, perhaps an adaptive display might be successful. The display could adapt based on where the pilot was in the approach, or could be more sophisticated and track pilot workload through physiological sensors, or could just have several modes that could be selected by the pilot.

One pilot said he would prefer a hazard indicator that was not in the visual field. Another stated that night operations were more important than day VFR (Visual Flight Rules), and that the indicating system must be studied at night for it to be useful. Night operations would be another fertile area for future research.

Numerous pilots commented on the quality of ART's flight simulation. "The simulation was good... in the [simulator] we use, as soon as you get off the ground, you punch the autopilot." Another said, "It's an order of magnitude better than any others I have experience with."

One pilot mentioned "sensor fusion" – a "hot topic in avionics research." This refers to the technique of melding data received from sensors (such as forward-looking infrared sensors or radar altimeters) with each other or with synthetic vision displays [25]. The results of this study

suggest the potential benefits of integrating visual hazard indicators with out-the-window views or synthetic vision systems.

Many pilots spontaneously mentioned helicopter accidents that they felt could have been avoided if the pilots had had access to a system like this one. One pilot mentioned the Mount Hood Pave Hawk crash in 2002, where a helicopter in the process of rescuing nine hikers trapped in a crevasse on a mountaintop suddenly crashed [26]. The weather was clear and sunny, but there were gusty winds, as is typical around a mountaintop. This pilot believed that unseen turbulence and/or downdrafts beyond the capability of the helicopter were the likely causes of the crash.

Another commented that in his work as a medevac pilot, he hated landing on top of Stanford Hospital, "especially at night." "There's always a vortex there," he said.

One pilot had a relative who flew helicopters in firefighting. Backdrafts and up- and downdrafts cause tremendous dangers for firefighting pilots. A system like this "could really make a difference," according to this pilot.

Conclusions and Further Work

Based on the results of a flight simulation usability study, we believe that simple, real-time visualization of airflow may improve helicopter pilot landing performance. The use of a simple, static visualization of airflow hazard location and severity leads to a significant decrease in crash rate for a critical class of landings (those where landing is permitted, but difficult). It also appears that the visual system does not distract the pilots nor cause degradation in their landing performance. Power spectrum analysis of lateral cyclic position during the simulated landing runs also points to a reduction in pilot workload with the hazard visualization system. Additionally, pilot feedback was generally favorable to the system. Further studies are called for to verify these results.

Acknowledgments

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